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"THEORETICAL MODELS OF GAS DYNAMICS AND STAR FORMATION IN INTERACTING RING GALAXIES

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INTRODUCTION

This report will be limited to a brief summary of the results of the project, since most of the work is detailed in published papers or in papers submitted for publication. These papers are listed in the reference list at the end of this report (and copies are attached in some cases).

However, before reviewing specific accomplishments, I think it is worthwhile to summarize some of the background and general goals of the project. The primary goal of this project has been to advance the theory of wave-driven star formation in galaxies, which is believed to be a very important process in their evolution. Because galaxies are inherently complex systems with many degrees of freedom (e.g. $> 10^{11}$ stars), this problem has many difficult aspects. Even though the basic theory of small-amplitude spiral density waves was developed more than two decades ago, and there has been much progress since then, but many questions remain unanswered.

Interacting galaxies have attracted a good deal of attention in the years since Toomre and Toomre's (1972) seminal paper, because both observations and numerical modeling suggest that strong waves can forced within galaxies as a result of such encounters. Thus, interacting galaxies offer a fairly unique opportunity to compare theory and models of nonlinear waves in galaxies to observations. Moreover, if interactions were indeed more common in the past, then waves driven by interactions may be, by themselves, an important force in galaxy evolution.

There have been many developments in this field since the proposal for this project was written in the spring of 1986. It was at about this time that the IRAS results and first statistical analyses were becoming widely disseminated. These results had a profound impact, especially in satisfying most astronomers' that mergers and interactions do induce strong bursts of star formation in galaxy nuclei. Unfortunately, IRAS did not have the resolution to address the question of more extended star formation in galaxy disks, except in the most nearby galaxies. Moreover, most of the nuclear starbursts are hidden by thick layers of absorbing dust, which precludes observations of them in many other wavebands, and allows confusion between starbursts and active (quasar-like) nuclei.

Without high-resolution, far-infrared observations, progress in understanding the weaker, extended, wave-driven star formation has been slower. However, because the obscuration is lower in galactic nuclei, near-infrared and optical CCD array data are also crucial to constraining models and theories. Such observations were pioneered at NASA's IRTF, and new generations of CCD arrays have pushed the resolutions and sensitivities of instruments a long way in the last few years. With these new ground-based capabilities, with more space ultraviolet capabilities (e.g. from the Hubble telescope), and ultimately with the high-resolution infrared capabilites of SIRTF, we can expect a wealth of new data to drive theoretical work in this field in the coming decade. Hopefully there will be a good deal of progress in understanding the different dynamics of the collisionless (stellar) and collisionless (gaseous) components in nonlinear waves in galaxies, though the difficulties in interpreting observations on the basis of inevitably idealized models must be remembered.

On the other hand, until our understanding of the physics of star formation improves, we can expect that this deficiency will slow our progress in understanding large-scale, wave-driven star formation. It is becoming recognized that it may be more productive to reverse the problem. and use the phenomenology of star formation in waves as a constraint on the possible physical processes.

In this project we have adopted the philosophy that it is best to study a few of the simpler cases in detail, and later attempt to generalize these cases. The cylindrically symmetric collisional ring galaxies are a paradigm. In the simplest cases, rings are essentially a one-dimensional (cylindrical) wave, and so their dynamics should be even simpler than classical spiral waves. They are generally well-separated from the galaxy nucleus, so they can be observed with modest angular resolution. However, ring waves are not as simple as we thought at the outset of this project. One of the chief results of our work during the last three years is that there can be much variety among the symmetric collisional rings. Less of a surprise is the fact that morphological variety is greatly increased when we also consider slightly asymmetric collisions. Nonetheless, we have also made significant progress in the last few years towards a physical classification of the stellar waves in disks following asymmetric collisions. Highlights of these results will be summarized in the following section.

PROJECT ACCOMPLISHMENTS

a) Symmetric Rings: Hydrodynamics and Star Formation

The project began with the completion of a series of one and two dimensional hydrodynamics simulations of a ring wave in interstellar gas disks. These calculations included nonlinear source terms to model the effects of interstellar cloud interactions and star formation, as well as the spatial-temporal gas flow. The details and the results of these simulations are given in publications 1-3 and 5 in the list below. Although the cloud interaction terms are quite idealized, the simulations are very relevant to IRAS data (which had already indicated a high star formation rate in ring galaxies), near-infared array (e.g. IRTF) data, and ultimately SIRTF data. Specifically, the model assumes that vigorous star formation is a density threshold phenomenon, and it predicts that if the gas density is pushed much above that threshold star formation will proceed in a strong burst mode. This starburst ring picture is in accord with observations to date, but these are quite limited compared to the infrared array data that will become available in the near future.

If ring galaxies are a density wave paradigm, and more data is available for comparison, I hope and expect that other models of cloud interactions and star formation will be tested in this application. Pubs. 1 and 2 may serve as a prototype for such studies.

Unfortunately, the numerical method used in these simulations could not be readily adapted to model the complexities of true three-dimensional collisions, including gas ejection from the target disk, and multiple collisions and mergers between the colliding galaxies. (In fact, the first two processes were explored with the cloud fluid code in the symmetric case. Some of this work is discussed in pubs. 9, 14.) Thus, in the final year of the project we began developing a smoothed particle hydrodynamics (SPH) algorithm, like those used by Hernquist, Lattanzio and others. By the end of the project we were working with a two-dimensional version of the code in a fixed gravitational potential. We expect that the code will be a very useful tool in future work.

b) Symmetric Rings: Stellar Dynamics

In order to begin to understand the star formation history in rings or other waves photometric colors or spectra are used to determine the relative numbers and distribution of old and young stars. This is made difficult by the fact that populations old red giants have nearly the same observed properties as young red supergiants. Moreover, early in the project we realized that we did not have a sufficiently clear idea of the stellar dynamics in rings to be able to predict the distribution of the old stars as a function of collisional and structural parameters. The basic epicyclic oscillation kinematics were clear from Toomre's work in the seventies. To further our understanding in this area we proceeded in two directions - numerical and analytical. The latter developed into a successful marriage of Toomre's kinematical model with Arnold, Shandarin and Zeldovich's "pancake" theory of caustics in galaxy formation. The resulting theory can describe almost all of the structure in restricted three-body simulations of single-pass collisions, even with multi-component (bulge-disk-halo) potentials (pub. 10). The available N-body simulations show very similar structure, though no detailed studies have yet been done.

P. Lotan pushed ahead with the restricted three-body simulations to model multiple collisons and capture of the companion galaxy as a result of the effects of dynamical friction. Even in the symmetric case where the companion moves almost entirely along the rotation axis of the target disk there are qualitative differences from single-pass collisions. As described in pub. 14, two sets of rings are generated in multiple collisions. The first set is like those produced in a single collision with a disturbance amplitude equal to the combined amplitude of the multiple encounters. The second set consists of thin, virtually stationary rings that have no analogue in single collisions. These phenomena can also be explained with the simple kinematic model. Thus, it appears at this point that we have quite a good understanding of the stellar dynamics of nonlinear, symmetric rings. (One notable exception is the case of ring-making collisions between comparably sized galaxies. In our analytic work it is assumed that the companion is less massive than the target disk galaxy.)

c) Slightly Off-center Collisions

Because of the special symmetry required to produce a ring in a collision between galaxies symmetric rings are expected to be relatively rare objects, and observations confirm this. To increase our observational sample, and generalize our understanding of the dynamics, we are naturally lead to the study of slightly off-center collisions. Collisional morphologies are very sensitive to impact parameter, so this is a large area of study.

Wallin and Struck-Marcell (pub. 6) studied one particular topic in this area - the case of collisions with impact parameter greater than zero, but still less than the scale-length of a substantial bulge component. Restricted three-body simulations showed that the asymmetric rings in this case appear more fragmentary, resembling those in the so-called shell galaxies. The simulation morphologies also resemble the "ripples" in galaxies studied by Schweizer, who suggests that in some cases these are the result of accretion of material in tidal encounters. Our models suggest that it is difficult in some cases to distinguish between these two possible causes of "ripples".

If the impact parameter is comparable to the scale-length of disk-bulge potential, the waves that propagate through the disk are much more asymmetric. In many cases they no longer resemble symmetric rings, and indeed have a very different phase-space topology. Nonetheless, a good deal of insight into the structure of these waves can be gained by extending the kinematic model mentioned above to this case. Semi-analytic calculations of the kinematic model led to the recognition that the asymmetric waves are all examples of the elementary catastrophes (caustics) of catastrophe or singularity theory. This recognition not only provides important theoretical insights into the evolution of these waves, but also yields some specific observationally verifiable predictions. The results are described in pubs.7, 12 and have been presented at several meetings recently. I believe that this will be an important area for further study.

d) Star Formation in Tidal Tails and Other Extended Features

In 1985-1987 J. Schombert (Univ. Michigan) and Wallin carried out multi-color optical and near-infrared observations of faint tidal features in about two dozen interacting galaxies selected from the Arp atlas. Though somewhat outside the scope of this project, and not directly supported through it, this work did provide very important observational input. Specifically, this sample provided evidence for ongoing star formation in tidal structures, and even enhancements of star formation in some cases. These conclusions are based in part on calculations with a color evolution program, and some new techniques for analysing two-color diagrams, developed by

Wallin and Struck-Marcell for the analysis and interpretation of these observations (see pub. 8).

Several galaxies with tidal tails were included in this observational sample. As part of his thesis work Wallin also carried out a series of high-particle-resolution, restricted three-body simulations of the evolution of density enhancements in tidal tails. In the end these simulations drew together our work in several different areas. The simulations showed that the most important "density enhancement" is a caustic wave like those discussed in the previous section, which propagates along the tail. In planar interactions the wave compression is high, and enhanced star formation is expected. In nonplanar interactions the wave is three-dimensional, the compression is less, and star formation may not be enhanced (see pub. 15). There was good agreement between the tail morphologies in the observations and the simulations.

e) Radial Distribution of Gas in Late-type Galaxy Disks

In constructing numerical models of interacting galaxies one always faces questions or choices in setting up the initial unperturbed galaxies. There are standard choices for the density profiles of the stellar disk, bulge and dark matter halo, which are reasonably well-grounded in observation. To date, the observational data have not clearly suggested a "standard" surface density profile for the disk gas. The impression given by 21 cm observations is that there is a wide variety of such distributions. This is clearly an important model input. A wealth of new data on the molecular component of the gas have recently appeared in the literature. Struck-Marcell decided to undertake the task of assembling the data for gas-rich, late-type galaxies, to see if a more coherent picture of the gas distribution would emerge from more complete data. This project is somewhat of a diversion from the original program of the grant. However, the possibility that these results would lead to the elimination of an arbitrary function in the initialization of numerical models strongly motivated the digression.

This hope appears to have been at least partially realized. It was found that in the flat rotation curve region of late-type disks the hydrodynamic equations have a unique steady state surface density profile (of 1/r form), in excellent agreement with the observations. Preliminary simulations with the SPH code confirm the tendency of the gas to relax to this profile. Analytic solutions of the equations with subsonic radial flows to balance gas consumption or expulsion from a central galactic fountain were also derived. These results are detailed in pub. 13.

SUMMARY

In anticipation of the new observational developments discussed in the introduction, the bulk of the work we originally proposed to carry out consisted of numerical, cloud fluid type models, in one and two dimensions, of the gas dynamics and star formation in interacting ring galaxies. In part because of the time delay between submission and funding, most this work in one dimension and some in two dimensions was completed relatively early in the project (see above). Although we continued to persue this work at a modest level of activity, there was a change of emphasis near the middle of the 3-year term. There were several reasons for this change. The first was that there were too few data available to test and constrain the several fairly arbitrary parametrizations used in the cloud fluid model. (Lacking a general theory of star formation, parametrized phenomenological models are the only way to proceed at present.) The numerical calculations made some definite predictions, as a function of these parametrizations, and it seemed best to wait to test these against observation before trying to refine our model of star formation and its feedbacks to the interstellar gas.

Secondly, we also felt a need to significantly upgrade and generalize our computer codes. The FCT hydrodynamics algorithm had significant limitations when applied to multi-dimensional simulations of galaxy interactions. As described above, we have begun to work with an SPH algorithm, which seems considerably more flexible. Equally important was the need to better understand the stellar dynamics along with the hydrodynamics. Several other groups have begun to carry out full N-body simulations of galaxy collisions, including ring-making cases. We opted not to duplicate that work (though we hope to use the results), but rather to persue the more heuristic analytical and restricted three-body calculations described in b) above to get at least a qualitative understanding of the behavior of the stars in a wide variety of cases. The results of this work are predictions of the relative distribution of old stars versus the gas and newly formed stars, which can be checked against observation.

A final point, new and exciting research opportunities appeared in two areas during this project. The first was the realization that it was possible to study nonlinear stellar density waves analytically with the caustics formalism, at least in the kinematic approximation. The second was the discovery that hydrodynamic forces might constrain the radial structure of the interstellar gas in galaxy disks in ways not previously realized. Work in these areas occupied a substantial amount of the PI's time by the end of the project term. Both these discoveries have opened large areas for further research. The understanding gained in these areas will provide a better foundation for, and probably simplify, a renewed attack on the hydrodynamics and star formation problems.

PERSONNEL

Curtis Struck-Marcell, P.I.

Pnina Luban-Lotan, R.A.
John F. Wallin, R.A.
Allan Sommerer, R.A. (supported for work on this project July - August 1989 only)

REFERENCES

Papers published (or in press).

1. Appleton, P.N., and Struck-Marcell, C., "Models of Ring Galaxies. I. Growth and Disruption of Clouds in the Expanding Density Wave", Astrophys. J. **318**, 103 (1987).

2. Struck-Marcell, C., and Appleton, P.N. "Models of Ring Galaxies. II. Extended Starbursts", Astrophys. J. **323**, 480 (1987).

3. Struck-Marcell, C., Scalo, J.M., and Appleton, P.N., "Cloud Fluid Models of Gas Dynamics and Star Formation in Galaxies", published in the proceedings of the IPAC Conference on "Star Formation in Galaxies", ed. C.J. Lonsdale Persson (Washington: NASA) (1987).

4. Appleton, P.N., Ghigo, F.D., van Gorkum, J.H., Schombert, J.M. and Struck-Marcell, C., " A Giant Intergalactic Bubble Near Arp 143", Nature **330**, 140 (1987).

5. P.N. Appleton and C. Struck-Marcell, "Are Starbursts the Result of the Fine Tuning of Dynamical Timescales?" in Third International IRAS Conference, "From Comets to Cosmology", ed. A. Lawrence, (1988).

6. John F. Wallin and Curtis Struck-Marcell, "A Collisional Model for the Formation of Ripples in Early-Type Disk Galaxies," Astron. J. **96**, 1850 (1988).

7. Struck-Marcell, C., "Two-dimensional Caustics in Disturbed Galaxy Disks", Astron. J. **99**, 71 (1990).

8. J. M. Schombert, J. F. Wallin, and Curtis Struck-Marcell, "A Multicolor Photometric Study of the Tidal Features in Interacting Galaxies", Astron. J. **99**, 497 (1990).

9. Pnina Luban-Lotan and Curtis Struck-Marcell, "Classes of Ring Galaxies Generated by Dynamical Friction, proceedings of the workshop "Evolutionary Phenomena in Galaxies", published in Astrophys. Space Sci. **156**, 229 (1989).

10. Curtis Struck-Marcell and Pnina Lotan, "The Varieties of Symmetric Stellar Rings and Radial Caustics in Galaxy Disks", in press for the Astrophys J., July, 1990.

11. Curtis Struck-Marcell, "Radial Profiles of Gas in Late-Type Galaxy Disks", in the proceedings of "The Second Wyoming Conference on the Interstellar Medium", July, 1989, in press.

12. Curtis Struck-Marcell, "Caustic Waves in Galaxy Disks Produced in Collisions with Low Mass Companions", contribution to the proceedings of I.A.U. Colloquium no. 124 "Paired and Interacting Galaxies".

Abstracts of papers presented at meetings or conferences.

J.F. Wallin, J.M. Schombert, and C. Struck-Marcell, " Arp 227: A Case for Tidally Formed Shells", Bul. Amer. Astr. Soc. 19, 1062 (1987).

Curtis Struck-Marcell and P.N. Appleton, "Models for the Ring and Plume in Arp 143," Bul. Amer. Astr. Soc. 19, 1108 (1987).

Pnina Luban-Lotan and C. Struck-Marcell, "Effects of Dynamical Friction on Colliding Ring Galaxies," Bul. Amer. Astr. Soc. 19, 1109 (1987).

Pnina Luban-Lotan, "Box-Shaped Galaxy Formation via Collisional Heating of a Cold Disk," Bul. Amer. Astr. Soc. 20, 699 (1988).

John F. Wallin and Curt Struck-Marcell, "Photometric Evolutionary Models of Ring Galaxies," Bul. Amer. Astr. Soc. 20, 700 (1988).

Papers submitted.

13. Curtis Struck-Marcell, "Hydrodynamic Constraints on the Radial Structure of Late-Type Galaxy Disks", submitted to the Astrophys. J.

14. Pnina Lotan and Curtis Struck-Marcell, "Effects of Satellite Multiple Passages and Merger on a Ring Galaxy", submitted to the Astrophys. J.

15. John F. Wallin, "Dynamical and Photometric Models of Star Formation in Tidal Tails", submitted to the Astrophys. J.

Theses

John F. Wallin, "Dynamic and Photometric Evolutionary Models of Tidal Tails and Ripples" (Ph.D. Aug. 1989)

Pnina Lotan-Luban, "Simulational Studies of the Formation and Properties of Ring Galaxies and Leading One-Arm Spirals Due to Galaxy Encounters" (Ph.D. to awarded Aug. 1990)